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# TERFENOL-D Lamination Process Cost Reduction
# Option I
# Final Technical Report

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Prepared By:
Julie Slaughter, Ph.D.
Principal Investigator

ETREMA Products, Inc.
2500 North Loop Drive
Ames, IA 50010

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## Phase I Option I Final Report


### Abstract

The effects of interlaminate resistance on eddy current generation in TERFENOL-D rods were studied. In the Phase I effort, an experimental study investigated the differences between solid drivers, drivers laminated with infinite resistivity epoxy, and drivers laminated with less-than-infinite resistivity epoxy. It was found that the rods with less-than-infinite resistivity epoxy performed significantly better than the solid rods, however, their performance was slightly less than the rods with infinite resistivity epoxy.[1]

In the present work, an idealized finite element model of eddy current losses was developed in order to study in detail the effect of epoxy resistivity on eddy current losses. These results were then compared with existing experimental results. With the data available, it was not feasible to compare actual eddy current power losses; however, changes in eddy current power losses could be compared.

The solid rods and rods with infinite resistance epoxy showed good agreement between experimental and analytical results. The rods with finite resistance epoxy did not show good agreement between experiment and theory. However, this discrepancy can be credited to errors in the measurement system. Finally, the results of both the experimental and analytical studies were used to develop a standard of interlaminate resistance. This standard will provide TERFENOL-D designers the opportunity to weigh the trade off between increased performance and increased material costs with infinite resistance joints.


### Introduction

The process of manufacturing laminated TERFENOL-D is costly and time consuming. This Phase I study was aimed at reducing the reject rate of the current lamination process and thus reducing the cost of laminated TERFENOL-D. In some instances, infinite resistance between lamina is required. These stringent requirements can lead to reject rates of finished drivers as high as 50%. Analytical calculations indicate that somewhat less than infinite interlaminate resistance provides significant eddy current reduction.

Phase I of "TERFENOL-D Lamination Process Cost Reduction" was an experimental study quantifying the difference in eddy current losses between drivers with finite interlaminate resistance and infinite interlaminate resistance. It was found that there is decreased performance in some drivers with finite resistance.[1]

The purpose of this Phase I Option for the "TERFENOL-D Lamination Process Cost Reduction" was to compare the experimental results from the Phase I work with analytical predictions. In addition, the analytical predictions were used to develop a performance function based on interlaminate resistance. This function quantifies the performance increase realized by requiring a given level of

interlaminate resistance. A standard will then be created for designers to weigh the trade off between performance increase and cost increase.

**Background**

This experimental study investigated the effects of less-than-infinite glue joints on eddy current losses. Test fixtures and methods were designed to compare solid rods and laminated rods with various interlaminate resistances. Initial results show a significant difference between solid rods and rods with less-than-infinite resistance. The difference between infinite and less-than-infinite interlaminate resistance was indicated but not quantified as some of the results were within variance of the test procedure. However, the difference between the infinite and less-than-infinite drivers was statistically significant for some of the test results[1].

**Experimental Results**

Several samples of TERFENOL-D were produced for Phase I of this work. The samples were 10 mm diameter and 35 mm length. In all 22 samples were produced, 5 solid rods, 5 laminated with infinite resistivity epoxy, 12 laminated with varying resistivity epoxies. The varying resistivity epoxies had the effect of changing the measured resistance between adjacent laminae.

A test apparatus was developed to test each of the rods and quantify their performance. A complete description of the test apparatus can be found in Reference 1. The test apparatus provided preload, DC bias field, and an AC drive field to the TERFENOL-D rod. Measurements from the test apparatus were input current, input voltage, and output acceleration. The samples were prestressed to 13.8 MPa, magnetically biased to 40,000 A/m, and driven with a sinusoidal field of +/-16,000 A/m over a frequency range of 4 kHz to 7.5 kHz.

The input current and voltage from the swept sine tests were used to find the impedance as a function of frequency. When plotted as a Nyquist plot (real vs. imaginary), the impedance should approximate a circle as it passes through resonance. Figure 1 shows a typical Nyquist plot of impedance. From the impedance, the potential efficiency[2,3] of the transducer can be calculated. A more complete description of the data analysis can be found in Reference 1.

Five swept sine tests were performed on each sample. Figure 2 shows the results from the potential efficiency calculations. Each column number represents a different TERFNOL-D sample. The y-axis is the value of potential efficiency in %. The lines extending from the top and bottom of the "box" represent the spread of the data for each sample. The horizontal line in the box represents the median of the data. From Figure 2 it can be seen that potential efficiencies of the solid rods do not overlap the laminated rods. The finite resistance rods and the infinite resistance rods have significant overlap. However, there is an indication that the infinite resistance rods have higher potential efficiencies. Reference 1 contains a more detailed description of the results.

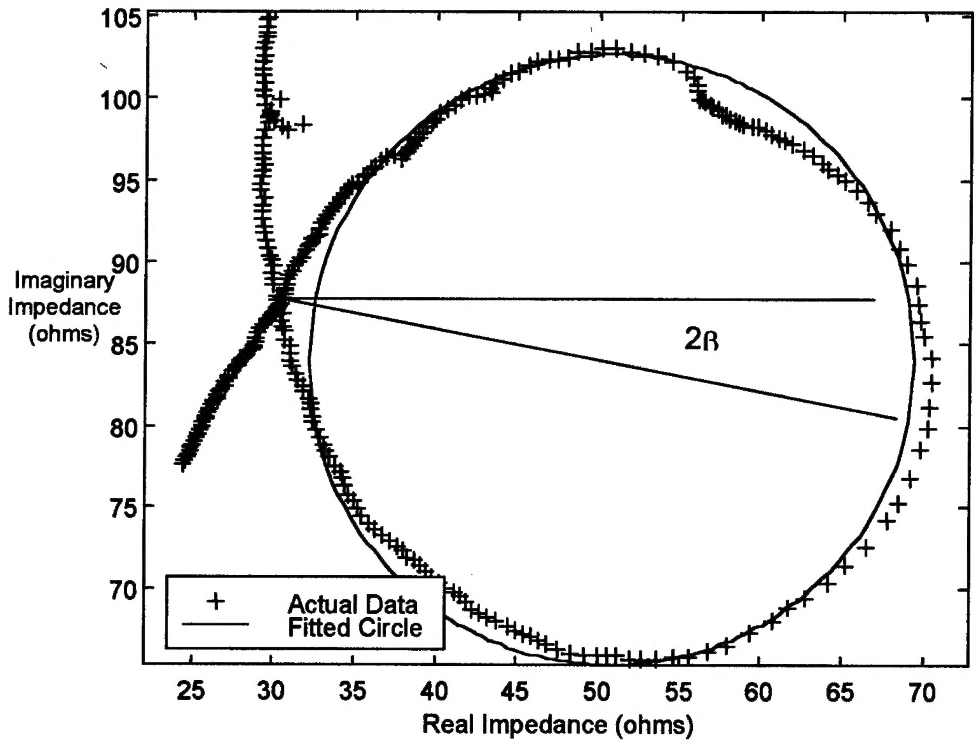


Figure 1. Typical Nyquist plot and a circle fitted to the data.

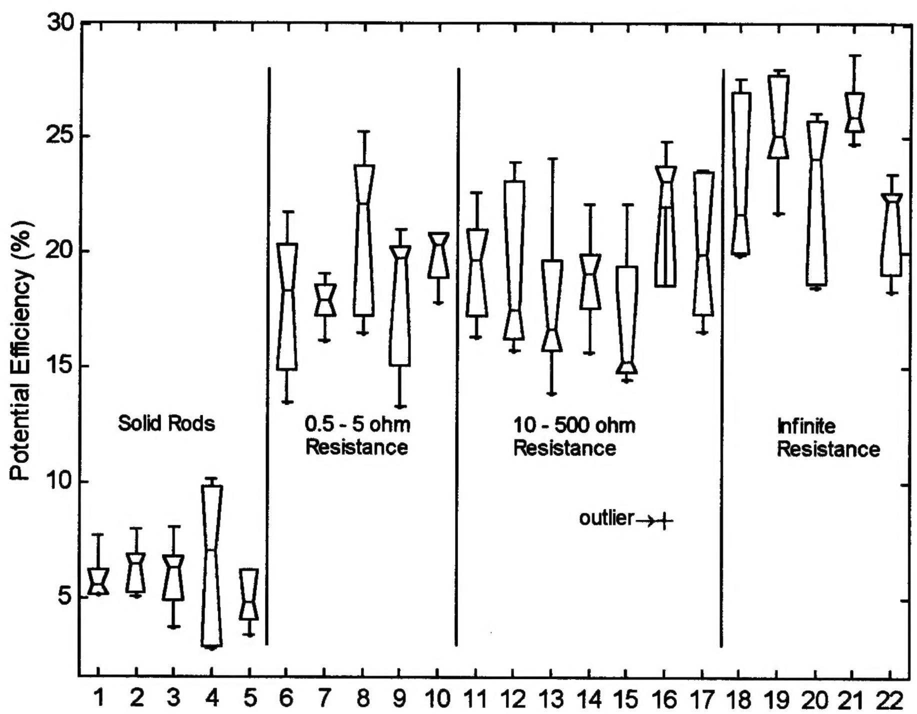


Figure 2. Box plot of potential efficiencies for all experimental samples.

Analysis of variance shows that all of the finite resistance tests have a 78.6% probability of being equal. This result means that the finite resistance data can be treated as one population with a single mean and a single standard deviation. Analysis of variance also shows that the infinite resistance tests only have a 5.8% probability of being equal. This result would indicate that the infinite resistance data should not be treated as one population. However, due to the limited amount of data available, the infinite resistance tests will all be treated as one population with a single mean and a single standard deviation. The solid rod tests have a 77.8% probability of being equal; therefore, these tests will be treated as one population also. Table 1 lists the means of the potential efficiencies for each type of driver.

| **Sample Description** | **Mean Potential Efficiency** |
|---|---|
| Solid rod | 0.060 |
| < infinite resistance | 0.190 |
| infinite resistance | 0.238 |

Table 1. Mean of potential efficiency for all samples.

The input power into the test system is distributed amongst various losses and mechanical output. These losses can be divided into several categories such as: hysteresis loss, electromagnetic loss, ohmic loss, eddy current loss, and mechanical damping amongst others. The focus of this study will be the eddy current losses. For the test system it is assumed that all losses except eddy currents are constant from one sample to the next. In order for this assumption to be valid many criteria must be met:

1. Input power is constant.
2. Preloading and bias conditions are identical.
3. Magnetic hysteresis does not vary from sample to sample.
4. Permeability of the driver does not change significantly from sample to sample so as to cause the magnetic circuit to perform differently.
5. The temperature is constant from test to test.

Other criteria may also be necessary, but these are the most significant. During the testing phase, the input power, preload, magnetic bias, and temperature were monitored in order to ensure that these conditions were constant for the tests. The magnetic circuit was designed to be relatively insensitive to small changes in permeability. Finally, when possible, the samples were made from the same unfinished rod to ensure that the hysteresis losses were as close as possible from sample to sample.

Equation 1 is a power balance:

$$P_{in} = P_{mech} + P_{e.c.} + P_{other} \tag{1}$$

where $P_{in}$ is the input electrical power, $P_{mech}$ is the mechanical output power, $P_{e.c.}$ is the power lost to eddy currents, and $P_{other}$ is the power lost to other loss

mechanisms as described above. If Equation 1 is divided through by the input power, the equation is written in terms of ratio of energy in each output mechanism to the input power. The mechanical output power divided by the input electrical power is called the electromechanical efficiency. Equation 2 shows the "efficiencies" of each of the loss mechanisms.

$$1 = \eta_{mech} + \eta_{e.c.} + \eta_{other} \tag{2}$$

The potential efficiency as obtained experimentally from the Phase I study is a measure of the maximum possible electromechanical efficiency[2,3]. Ideally, what is desired is to calculate the percent difference in eddy current losses between an infinite resistance driver and a less-than-infinite resistance driver. However, this is equivalent to the percent difference in ratios from equation 2. Using equation 2 with subscript 1 indicating the first sample and subscript 2 indicating the second sample, the difference in eddy current losses can be shown to be equal to:

$$\eta_{e.c.2} - \eta_{e.c.1} = \eta_{mech1} - \eta_{mech2} \tag{3}$$

The potential efficiencies calculated from the experimental data will be used as a measure of the electromechanical efficiency. Using this calculation, the experimental difference in eddy current losses can be quantified. Because the "other" losses cannot be explicitly quantified, the actual value for eddy current losses cannot be obtained. However, as shown in equation 3, the difference between eddy current losses can be calculated.

The calculations of differences in eddy current losses will all be referenced to the case with minimum eddy current losses, i.e. infinite resistance joints. These results will be explored more fully in the **Comparison of Experiment and Theory** section.

**Analytical Results**

A commercially available finite element package, ANSYS 5.5, was used to perform the analytical eddy current loss calculations. An idealized 1/8-symmetry 3-D model was constructed using 5 materials and 6 separate components. The components were two TERFENOL-D slabs, an epoxy joint between the TERFNOL-D slabs, a copper coil, an air gap, and a magnetic return path. Figure 3 shows the entire 3-D model and Figure 4 shows only the TERFENOL-D and the epoxy. The material properties used are listed in Table 2.

| Material | Relative Permeability | Resistivity (Ω-m) |
|---|---|---|
| Air | 1 | N/A |
| TERFENOL-D | 2.5 | 5.8e-7 |
| Return Path | 300 | 3.3e-3 |
| Coil | 1 | 1.72e-8 |
| Epoxy (solid rod) | 2.5 | 5.8e-7 |
| Epoxy (variable resistivity) | 1 | 1.33e-6 through 2.22e+6 |

Table 2. Material properties used in Finite Element Model.

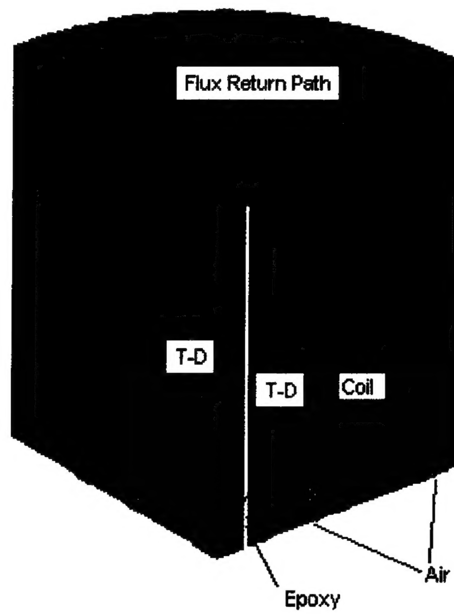


Figure 3. 3-D Finite Element model of TERFENOL-D rod and epoxy.

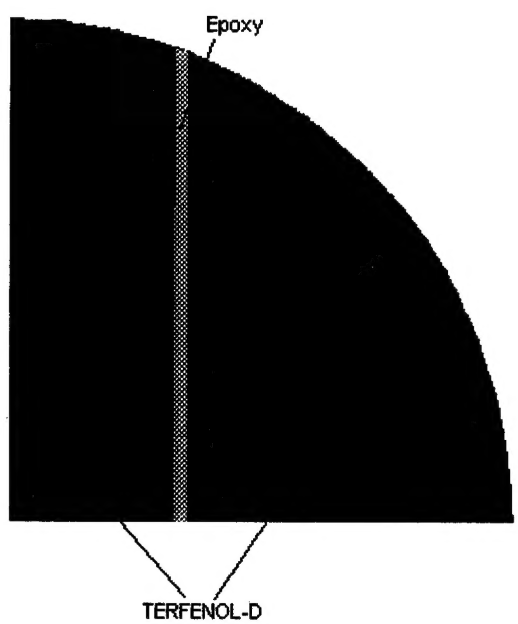


Figure 4. End view of TERFENOL-D and Epoxy.

The model was created with an idealized magnetic circuit that had no air gaps in it. This idealization was not representative of the test system used in the experimental portion; however, only the eddy current losses in the TERFENOL-D were studied. A harmonic excitation at 6,000 Hz was applied to the coil. Because the model was only run at a single frequency, a constant permeability was used. This situation deviates from the experiments in that a swept sine test was performed and the permeability of TERFENOL-D changes with frequency.[4] The excitation current was kept constant for every case run. The input current resulted in an average magnetic field of 36,000 A/m in the case with high resistivity epoxy (2.22e+6 Ω-m) and an average field of 28,900 A/m in the case with the solid rod. Several cases between the solid rod and the high resistivity epoxy were run in order to generate a curve.

In order to verify the numerical results calculated from the finite element model, the eddy current power losses were compared against calculations from the well-known eddy current equation,[5]

$$P_{ec} = \frac{(\pi B d f)^2}{\beta \rho} V \tag{4}$$

where $P_{ec}$ is the power lost to eddy currents in Watts, $B$ is the maximum magnetic induction, $d$ is the cross-sectional dimension (diameter for cylinders, thickness for laminations), $f$ is the frequency of operation, $\beta$ is a geometrical factor (16 for cylinders, 6 for laminations), $\rho$ is the resistivity, and $V$ is the volume of the lamination or cylinder. For the infinite resistivity laminated driver the eddy current power loss from equation 4 is 37.6 W. The eddy current power loss calculated from the finite element code is 32.7 W. Equation 4 does not account for such occurrences as eddy current shielding and assumes uniform magnetic field penetration. The thickness of the laminations is such that some eddy current shielding would occur. These factors can account for the differences in eddy current losses calculated from the FEA and Equation 4. For the solid cylinder, the eddy current shielding would be more significant; therefore, the eddy current losses calculated from the two methods would show less agreement. From Equation 4, the eddy current power loss is 154 W. The finite element method calculates the loss as 84.8 W. The finite element power calculations are assumed to be more accurate because no assumptions are made about eddy current shielding or uniform magnetic field penetration.

Figure 5 shows the normalized power loss as a function of resistivity. The results indicate that if the joint resistivity is greater than 2.22e-2 Ω-m the full benefits of the epoxy joint are realized. This resistivity corresponds to a measured interlaminate resistance of 0.01 Ω for the given geometry. The actual resistance value required for full benefits of the epoxy joint will vary with sample and joint geometry. However, provided the epoxy thickness is the same in all cases, the resistivity required for full benefits should be the same.

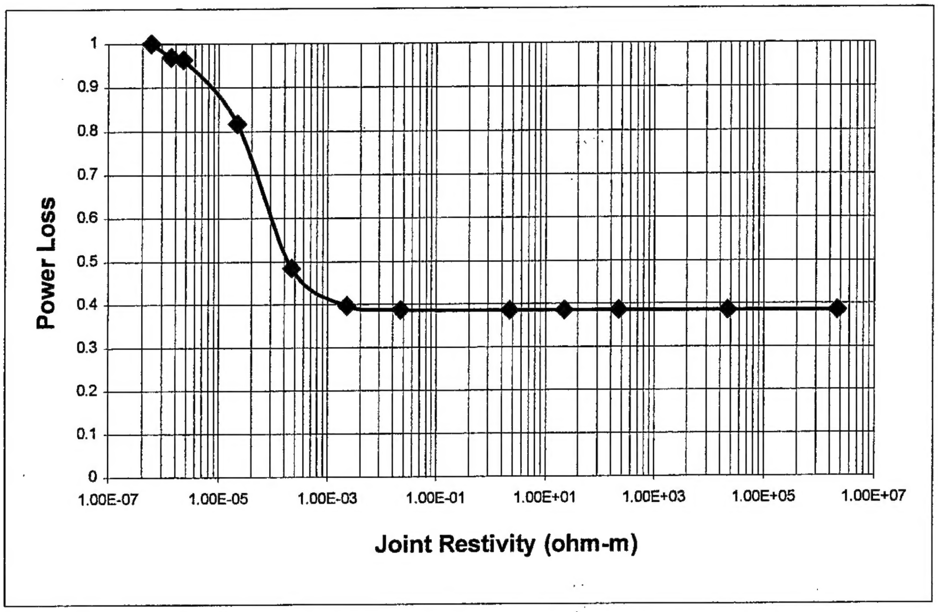


Figure 5. Power loss normalized to solid rod power loss.

The relationship between resistivity and resistance is given by Equation 5.

$$R = \frac{\rho t}{dh} \tag{5}$$

where $R$ is the measured resistance, $\rho$ is the resistivity, $t$ is the thickness of the epoxy, $h$ is the length of the rod, and $d$ is epoxy dimension across the rod face. The $dh$ term is the epoxy area bonded to a TERFENOL-D lamina.

The total power in the TERFENOL-D rod for the finite element model can be divided into the eddy current losses and the magnetic power. There are no hysteresis or mechanical losses in the finite element model. The RMS magnetic power can be calculated using:

$$P_{mag} = \frac{1}{2}\mu_0 \mu_r \omega V H_{pk}^2 \tag{6}$$

where $\mu_0$ is the permeability of free space, $\mu_r$ is the relative permeability, $\omega$ is the circular frequency in radians, $V$ is the volume of TERFENOL-D, and $H_{pk}$ is the peak magnetic field. The total input power to the TERFENOL-D can be obtained by adding the eddy current losses and the magnetic power. Finally, the fraction of eddy current power losses can be determined by dividing the total eddy current losses in the TERFENOL-D by the total input power.

$$\eta_{ec} = \frac{P_{ec}}{P_{total}} \tag{7}$$

Losses in all other components can be ignored for similar reasons to those given for the experimental results. From this information, the differences in eddy current losses can be calculated similar to the calculation for the experimental data. Table 3 summarizes the fraction of power lost to eddy currents for each different epoxy resistivity.

| Resistivity (Ω-m) | Resistance (Ω) | Fraction of Eddy Current Power Loss |
|---|---|---|
| Solid Rod | N/A | 0.293 |
| 1.33E-06 | 6e-7 | 0.284 |
| 2.22E-06 | 1e-6 | 0.282 |
| 2.22E-05 | 1e-5 | 0. 239 |
| 2.22E-04 | 1e-4 | 0. 142 |
| 2.22E-03 | 1e-3 | 0.116 |
| 2.22E-02 | 1e-2 | 0.113 |
| 2.22E+00 | 1 | 0.113 |
| 2.22E+01 | 10 | 0.113 |
| 2.22E+02 | 100 | 0.113 |
| 2.22E+04 | 1e4 | 0.113 |
| 2.22E+06 | 1e6 | 0.113 |

Table 3. Fraction of eddy current power loss for various epoxy resistivities.

**Comparison of Experimental and Analytical Results**

As described in the Experimental Results section, a quantitative measure of the eddy currents is not possible with the existing experimental data. However, it is possible to find the difference in fractions of power lost to eddy currents. Table 4 summarizes these calculations for both experimental and analytical results.

The results in Table 4 show the same trends experimentally and analytically. The results for the solid samples are nearly identical. In fact, the results are well within any existing experimental error. However, the experimental finite resistance sample shows significantly more eddy current loss than the corresponding finite element results.

| Resistivity (Ω-m) | Interlaminate Resistance (Ω) | Experimental $\eta_{ec1} - \eta_{ec2}$ | Analytical $\eta_{ec1} - \eta_{ec2}$ |
|---|---|---|---|
| Solid Rod | Solid | 0.178 | 0.180 |
| 1.33E-06 | 6.00E-07 | | 0.171 |
| 2.22E-06 | 1.00E-06 | | 0.169 |
| 2.22E-05 | 1.00E-05 | | 0.126 |
| 2.22E-04 | 1.00E-04 | | 0.029 |
| 2.22E-03 | 0.001 | | 0.003 |
| 2.22E-02 | 0.01 | | 0.000327 |
| 2.22E+00 | 1 | 0.048 | 3.28E-06 |
| 2.22E+01 | 10 | | 3.28E-07 |
| 2.22E+02 | 100 | | 3.29E-08 |
| 2.22E+04 | 10000 | | 2.76E-10 |
| 2.22E+06 | 1000000 | 0 | 0 |

Table 4. Difference in eddy current fraction for various experimental and analytical cases.

There are many potential causes for the differences. The variance in the experimental data is very large as was shown in Reference 1. Measurement of interlaminate resistance is a bulk measurement of a varying property. The distribution of silver particles in the epoxy may vary spatially in the rod assembly. Assuming that the potential efficiency is representative of the electromechanical efficiency may also introduce some errors. Due to these various mechanisms, the difference between experiment and theory for the finite resistance samples may not be significant. The experimental results for the finite resistance samples correspond more closely with an epoxy resistance of 1.0e-4 Ω than with the 1-10 Ω results.

The experimental results indicate that the interlaminate resistance should be on the order of 1 Ω in order to realize the full benefits of the lamination process. However, the analytical results indicate that only a very small interlaminate resistance, 1e-3 Ω, is needed to realize the full benefits of laminating. Because of the uncertainty in measurement of the interlaminate resistance and the uncertainty in the potential efficiency values, both the analytical and experimental results will be used to establish a standard for determining interlaminate resistance.

**Conclusions**

Both experiments and finite element calculations show a significant difference between solid rods and rods with less-than-infinite resistance glue joints. The benefits of the laminating process on eddy current losses are not nullified when a short exists between two laminae. In fact, the measured resistance can be quite low and still the full effect of laminations is achieved.

While there may be a slight difference between infinite resistance and less-than-infinite resistance glue joints, the current test system was not sensitive enough to make a conclusive statement. In addition to the variance of the tests, it was also found that the measurements of impedance were inaccurate due to equipment limitations. These limitations were addressed through more advanced equipment, however, there was no opportunity to repeat the measurements. Either more tests, a more sensitive test system, or an alternative test methodology would be required to draw conclusions about the difference between infinite and less-than-infinite glue joints. However, because of the limited scope of this study, these improved tests were not undertaken.

The finite element investigation of eddy current losses shows that the full benefit of the lamination process can be achieved if the epoxy resistivity is on the order of 1e-2 Ω-m. Unfortunately, resistivity is not a directly measurable quantity. The measured value will be interlaminate resistance. The value of resistance required to achieve full benefits of the lamination process will vary with geometry (Equation 5). For a very small piece of laminated TERFENOL-D (e.g. 4 mm diameter by 2 mm length) with a glue joint thickness of 0.1 mm, the measured

interlaminate resistance to achieve full benefits of the epoxy is 0.125 Ω. For a large sample (e.g. 64 mm diameter by 128 mm long) with the same epoxy thickness, the minimum interlaminate resistance required is 1.2e-4 Ω.

Due to the wide range of TERFENOL-D driver sizes available, the standard interlaminate resistance required must cover the entire range. As shown previously, the highest values of resistance are required for the smallest drivers. The smallest anticipated laminated driver at this time is 1mm diameter by 1mm length. The theoretical value of resistance required for this geometry is 1 Ω. However, because the experimental results for the finite resistance drivers do not agree closely with the analytical results, the required resistance value will be increased by a factor of nearly 100. **If the measured value of interlaminate resistance is greater than 10 Ω, the driver will be considered to meet the minimum standard requirements for laminated material.** However, if the designer wishes to require a higher value of interlaminate resistance, the cost of the drivers will increase accordingly.

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Julie Slaughter, Ph.D.

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ETREMA Products, Inc.
2500 North Loop Drive
Ames, IA 50010

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**13. ABSTRACT** ***(Maximum 200 words)***
For a summary of previous Phase I research see Contract N00140-98-C-1529, CLIN 0001AD, CDRL Item A004, Final Technical Report, dated 20 November 1998. In the present work, an idealized finite element model of eddy current losses was developed in order to study in detail the effect of epoxy resistivity on eddy current losses. These results were then compared with existing experimental results. With the data available, it was not feasible to compare actual eddy current power losses; however, changes in eddy current power losses could be compared.
The solid rods and rods with infinite resistance epoxy showed good agreement between experimental and analytical results. The rods with finite resistance epoxy did not show good agreement between experiment and theory. However, this discrepancy can be credited to errors in the measurement system. Finally, the results of both the experimental and analytical studies were used to develop a standard of interlaminate resistance. This standard will provide TERFENOL-D designers the opportunity to weigh the trade off between increased performance and increased material costs with infinite resistance joints.

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